

FORMATION OF SUPER-MASSIVE BLACK HOLES

WOLFGANG J. DUSCHL

*Institut für Theoretische Astrophysik,
Tiergartenstr. 15,
69121 Heidelberg, Germany
E-mail: wjd@ita.uni-heidelberg.de*

PETER A. STRITTMATTER

*Steward Observatory, The University of Arizona,
933 N. Cherry Ave.,
Tucson, AZ 85721, USA
E-mail: pstrittmatter@as.arizona.edu*

We show that the rapid formation of super-massive black holes in quasars can indeed be understood in terms of major galaxy mergers followed by disk accretion. The necessary short disk evolution time can be achieved provided the disk viscosity is sufficiently large, which, for instance, is the case for hydrodynamic turbulence, unlimited by shock dissipation. We present numerical calculations for a representative case. This general picture can account for (a) the presence of highly luminous quasars at redshifts $z > 6$; (b) for the peak in quasar activity at $z \sim 2$; and (c) for a subsequent rapid disappearance of quasars at later epochs.

1. Introduction

From their observed redshift distribution, luminous quasars are most prevalent at redshifts around $z \sim 2$ (Hasinger²¹; Fan et al.¹³). Recent discoveries have pushed back the limit at which galaxies and quasars appear in the young Universe to redshifts of $z \sim 6.6$ for galaxies (Hu et al.²²) and $z \sim 6.4$ for quasars (Fan et al.¹⁴, Willott et al.³⁸). These objects were, therefore, already present when the Universe was less than $\sim 10^9$ years old^a. Assuming that quasars are powered by accretion onto super-massive black holes (SMBH) at rates at or below the Eddington limit, luminosity measures from the Sloan Digital Sky Survey (Fan et al.¹³) and from the Chandra and XMM-Newton observatories (Brandt et al.^{6,7}), as well as IR spectroscopy (Willott et al.³⁸) require that black holes of mass $\geq 10^9 M_\odot$ are already present at this early epoch. This leads to the question of the origin of such SMBHs and, in particular, whether there is a viable way of forming them in the very short time scale permitted by the observational data.

^aWe take the following set of cosmological parameters: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_{\text{tot}} = 1$, and a corresponding age of the Universe of 13.5 Gyr

It has been argued that the presence of massive black holes can be understood in the framework of hierarchical merging, (e.g., Haiman & Loeb²⁰). We suggest the accretion disk model presents a viable alternative to the formation of super-massive black holes and retains the advantage that it also provides a natural explanation for the formation of jet outflows observed in many quasars.

In this contribution, we will argue that the quasar phenomenon is indeed a direct consequence of a *major merger* of (proto-)galaxies followed by high-efficiency disk accretion onto a black hole (c.f. Dopita¹¹ and references therein). We define such a merger to be the coalescence of two gas-rich galaxies of about equal mass resulting in the deposition of large amounts of gas in a disk close to the center of the merged galaxy (Barnes & Hernquist^{2,3}, Naab & Burkert²⁷, Barnes¹). We then examine the evolution of the disk through accretion driven by hydrodynamic turbulence unlimited by shock dissipation (Duschl, Strittmatter & Biermann¹², hereafter DSB) and show that the growth of a central black hole can occur in the requisite short time scale. We demonstrate that, even in the absence of massive BHs in the *merging* galaxies, it is possible to form a sufficiently massive BH in the *merged* galaxy in the required short time. While the importance of mergers for feeding quasars has been under discussion for some time (e.g., Stockton³⁷, Canalizo & Stockton⁸), we will show that major mergers can be instrumental both in *providing the fuel* and in *building the engine* that produces the quasar phenomenon. The general model also accounts for the absence of quasars at the current epoch.

2. The physical scenario

In the following, we make the robust assumption that, due to a major merger, tidal forces have driven a large amount ($10^{9...10} M_{\odot}$) of accretable matter into the central regions (within a few 10^2 pc from the center) of the newly formed merged galaxy. Detailed numerical model calculations (Barnes & Hernquist^{2,3}, Naab & Burkert²⁷, Barnes¹) have shown that in such mergers, (*a*) the ISM loses most of its angular momentum relatively rapidly, approximately on the dynamical timescale of the galaxies involved, but (*b*) still retains too much angular momentum to be immediately available for formation of or accretion into a black hole. We assume that there is no preexisting super-massive black hole at the center of the merged galaxies, though we allow on numerical grounds for a comparatively small seed black hole. This scenario provides the starting point for our model.

We envisage that this self-gravitating disk of gas (and dust) will evolve as follows. First material will accrete towards the center, whether or not a seed (low mass) black hole is present, and will be able to radiate all energy liberated through viscous dissipation. The significant mass flow towards the disk's center (see next section for details) will lead to (*a*) the formation of a seed black hole (if none was present before), and (*b*) an initial phase of Eddington-limited accretion into it. We assume that the black hole accretes at its Eddington rate as long as the disk delivers enough

mass to maintain this rate^b.

Ongoing accretion will deplete the mass of the accretion disk and thus decrease the mass delivery rate towards the black hole, while – at the same time – the black hole is growing in mass due to the same accretion process. Ultimately the mass flow rate from the disk to the black hole will become smaller than the Eddington accretion rate, *free accretion* will set in, and all incoming mass will be accreted by the black hole. At this stage, the accretion disk is still able to radiate all the energy liberated by viscous dissipation. In the course of this evolution, however, the accretion rate drops, both in absolute terms as well as in units of the corresponding Eddington accretion rate. When the actual accretion rate falls below roughly 0.3 % of the Eddington rate, the flow becomes advection dominated (Beckert & Duschl⁵), and the radiation efficiency of the accretion process falls very quickly by several orders of magnitude. The luminosity decreases correspondingly.

While the above scenario seems plausible for quasar evolution, the question is whether it provides a quantitative explanation for the observational data cited above. Earlier models (e.g., Shlosman, Begelman, & Frank³⁴) based on α -accretion disk models (Shakura & Sunyaev³³) led to excessively long evolution time scales (exceeding the Hubble time) for disks in the centers of AGN, thereby precluding the formation of SMBHs at early enough epochs. Consequently, various – mostly non-axisymmetric – processes (bars, spiral waves, etc.) were investigated in order to speed up the accretion process (e.g., Shlosman, Frank, & Begelman³⁵; Chakrabarti & Wiita⁹), even though disk models, because of their symmetry, provided a natural origin for the collimated jet outflows, which appear to be a frequent occurrence in quasars.

In the meantime DSB pointed out that experimental data on rotating fluids suggest an alternative, hydrodynamic origin of turbulence and hence a different viscosity prescription – β -viscosity – that would apply as long as the associated turbulent motions remained sub-sonic (see also Richard & Zahn³¹, Longaretti²⁶, and Richard³⁰). In the following section we investigate the evolution of accretion disks with such β -viscosity.

3. The model

We have carried out numerical calculations that model the evolution of an accretion disk resulting from a major merger. In addition to the standard set of time dependent accretion disk equations (see, e.g., Frank, King, & Raine¹⁷), we take self-gravity into account through Poisson's equation. The thermal properties of the disk are treated with a single zone approximation (for a discussion of the validity of this approximation see Huré & Galliano²³). We assume the disk to be azimuthally

^bWe note that the strength of the Eddington limit on the accretion rate is still not settled (e.g., Collin et al.¹⁰, Ohsuga et al.²⁸). Super-Eddington accretion, however, is not required in the present model to achieve the necessary time scales.

symmetric and geometrically relatively thin perpendicular to its rotational plane. For the initial distribution of the mass in the disk, we chose a radial distribution of the surface density $\Sigma \propto s^{-1}$ where s is the radial coordinate. If the mass flow rate to the black hole exceeds the classical Eddington limit, we allow the black hole to grow only at the corresponding Eddington rate.

For our models, we use the β -viscosity parameterization suggested by DSB

$$\nu = \beta s v_\varphi \quad (1)$$

whenever the turbulent velocity $v_{\text{turb}} \sim \beta^{1/2} v_\varphi$ and local sound velocity c_s in the resultant flow satisfy the condition that

$$v_{\text{turb}} \leq c_s . \quad (2)$$

Laboratory experiments suggest a value of β in the range $10^{-3} < \beta < 10^{-2}$, where β^{-1} corresponds to the critical Reynolds number \Re_c for the onset of turbulence in the flow. The corresponding accretion and dynamical time scales, τ_{accr} and τ_{dyn} , are given by

$$\tau_{\text{accr}} = s^2 / \nu = (\beta \omega)^{-1} = \beta^{-1} \tau_{\text{dyn}} = \Re_c \tau_{\text{dyn}} . \quad (3)$$

In this framework it can be shown (Duschl & Strittmatter, in prep.) that the thermal timescale is sufficiently long compared to the dynamical timescale to ensure stability of the disk against fragmentation (Gammie¹⁸, Rice et al.²⁹).

We use an explicit finite-difference scheme. At the inner radius ($s = s_i$), we allow any material either to be accreted onto the central black hole (at or below the Eddington rate) or to be lost from the system. We also set the surface density $\Sigma(s = s_i) = 0$, or equivalently the viscous torque $G(s_i) = 0$. At the outer boundary of the disk, we assume angular momentum to be removed efficiently. We choose a fixed outer boundary at $s = s_o$ and set $\partial G / \partial s|_{s=s_o} = 0$, which removes angular momentum from the material at the required rate.

As a specific illustrating example, we consider the evolution of an accretion disk of initial mass $M_d(t=0) = 10^{10} M_\odot$, inner radius $s_i = 10^{16}$ cm, outer radius $s_o = 10^{20}$ cm, and viscosity parameter $\beta = 10^{-3}$, and follow the evolution of the mass of a central black hole. In the numerical model presented here, we have assumed, for convenience, the initial presence of a seed black hole mass of $10^6 M_\odot$. We have, however, calculated models with seed black holes between 10^2 and $10^7 M_\odot$, which lead qualitatively to the same results.

The resulting evolution of quasar luminosity and black hole mass are illustrated in Figure 1. For the first $3 \cdot 10^8$ years, the growth of the black hole mass is constrained by the Eddington limit. This time scale corresponds to Salpeter's³² growth time scale and as such depends on the initial mass of the central object at $t = 0$.

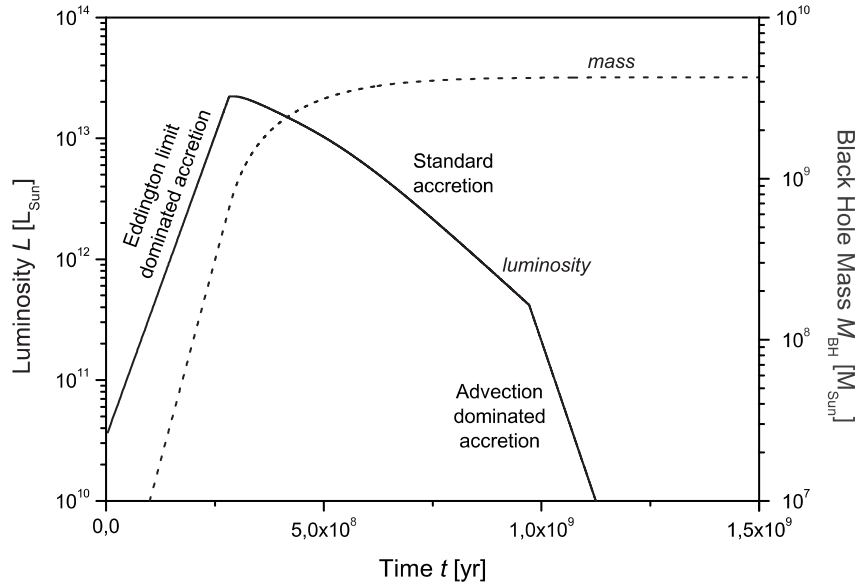


Figure 1. The evolution of the accretion luminosity (full line) and of the mass (dotted line) of a black hole in the center of an accretion disk with the initial parameters given in the text.

After that time, the free accretion period sets in, during which the central black hole is able to swallow all matter delivered by the disk. However, due to the decreasing disk mass (still large compared to the central black hole) the mass flow into the black hole slows down and the luminosity declines correspondingly. At the same time, due to an ever-increasing black hole mass, the limiting Eddington rate continues to increase. In this example, the free accretion phase lasts for $7 \cdot 10^8$ years. It comes to an end when the accretion rate falls below 0.3% of the Eddington rate and the flow becomes advection dominated (Beckert & Duschl⁵). While the accretion rate itself continues to fall slowly, the radiation efficiency of the accreting material drops drastically, and consequently so does the accretion luminosity. We note that the time spent at a luminosity exceeding one half the peak value is roughly $2.5 \cdot 10^8$ years, mostly in the post-peak era.

4. Discussion

Our results (Fig. 1) show that the luminous ($> 10^{11} L_{\odot}$), and hence readily detectable, phase of our proposed quasar model lasts $\leq 10^9$ years. While the precise duration of the black hole accretion phase will depend on the detailed parameters of the disk formed during the major merger, a typical timescale from the onset of

the disk evolution to the beginning of the advection dominated phase of $\sim 10^9$ years should be representative. The duration of the most luminous phase around the transition from the Eddington limited to free accretion is much shorter than 10^9 years, in qualitative agreement with recent observational results (e.g., Yu & Tremaine³⁹). This is significantly shorter than the interval ($\sim 10^{10}$ years corresponding to redshifts $1 < z < 5$) during which quasars are prevalent in the Universe. Within this model, therefore, the number density of quasars at different epochs is determined almost entirely by the rate of occurrence of major mergers. This question has been analyzed by several authors (e.g., Kauffmann & Haehnelt²⁴, Duschl & Horst, in prep.) and has been shown to peak at epochs corresponding to $z \sim 2$, a result that is consistent with the observed distribution of quasars (Hasinger²¹). The quasar with the currently highest known redshift, SDSS J1148+5251, at $z = 6.4$, seems to still be in the Eddington limit controlled regime (Willott et al.³⁸, Barth et al.⁴), in all likelihood not too far from its maximum luminosity. Taking all this evidence together, the model, therefore, seems to be broadly consistent with the available observational data.

For the above quasar scenario to succeed, it is essential to have an efficient accretion process so that a black hole can grow quickly and can produce the required luminosity. The accretion process also has to be efficient enough to accrete away most of the available gas and dust and thus lead to a rapid end of the quasar phenomenon due to a drop in both the accretion rate and in the disk's radiation efficiency. The time scales computed above for the various phases of β -disk evolution are substantially shorter than those previously derived for α -disk models.

The disk's viscosity is therefore the crucial quantity. As pointed out by DSB and by Richard and Zahn³¹, laboratory experiments indicate that the β -prescription is appropriate for turbulent viscosity in incompressible flows where the turbulence is clearly driven hydrodynamically. DSB suggested that this prescription is also appropriate in compressible flows, such as accretion disks, provided the turbulence remains sub-sonic so that shock dissipation is negligible^c. For internal consistency this model, therefore, requires that throughout the disk flow $\delta = v_{\text{turb}}/c_s = \beta^{1/2}v_\phi/c_s \leq 1$. In the calculations reported above, the ratio δ satisfies the condition $0.01 \leq \delta \leq 1$ throughout the disk and at all times, so that the model remains internally self consistent. As noted above this "hot disk" model also carries with it the consequence that the disk, while flattened, cannot be very thin and will be stable against fragmentation (Duschl & Strittmatter, in prep.).

We acknowledge that angular momentum can be removed rapidly from the disk through other mechanisms – usually involving non-axisymmetric instabilities – so that the β -disk model is not unique in providing rapid time scales. On the other hand, because of their symmetry, disk models do provide a natural scenario for the

^cDSB also show that in the case of shock limited turbulence (i.e., when the hydrodynamically driven turbulence would be super-sonic) in Keplerian disks, the α -prescription is indeed appropriate. This situation applies, for example, to the disks in cataclysmic variable stars.

generation of collimated jet outflows, which appear to be a frequent occurrence in quasars. It is noteworthy that while among local AGNs of the Seyfert type a larger fraction of the host galaxies may be barred than among non-active but otherwise similar galaxies, this fraction is clearly below unity (Laine et al.²⁵). This renders bar action as the (sole) driving mechanism of AGNs highly unlikely.

The model described above has been highly simplified, in that we have not treated star formation, mass-loss from the disk itself or the fate of matter that could not be assimilated by the black hole during the Eddington limited phase of disk evolution. In reality, a significant part of the material in a self-gravitating disk will be transformed into stars. However, the matter supply from the disk is more than sufficient to maintain an Eddington accretion rate for several 10^8 years. The essential features of the model will thus remain unless virtually all ($> 90\%$) of the disk material is transformed into stars. We will address the role of star formation in self-gravitating accretion disks in an upcoming paper (Duschl & Strittmatter, in prep.). In regard to mass loss from the disk, especially near the black hole, one may speculate that this provides an ideal source of material and energy to form a jet and a broad line region. It is also possible that the later (advection dominated phase) in which the thermal luminosity is small, may result in increased visibility of non-thermal jet emission and hence the blazar phenomenon towards the end of the quasar lifetime.

Given the short formation time scale for massive black holes, the present scenario obviates the need to postulate the existence of primordial SMBH in accounting for the quasar phenomenon. The model requires that quasars occur in galaxies which encountered major mergers so that in today's Universe, these galaxies must have massive ($10^9 M_\odot$ or more) central black holes. Galaxies, which never experienced a major merger, may harbor black holes of considerably smaller mass and may, therefore, still exhibit phases of more modest nuclear activity, for instance as Seyfert galaxies. Clearly as the strength of galaxy interactions varies so also will the observable characteristics of the merged galaxy (or post interaction galaxies). For example less accretable mass driven into a more extensive disk, would make the corresponding time scales of viscous evolution much longer and the central source less luminous. Such sources may well be associated with the faint, optically selected AGN population noted by Steidel et al.³⁶.

There is mounting evidence for a close relation between the mass of a central black hole, the bulge velocity dispersion (Ferrarese & Merritt¹⁶; Gebhardt et al.¹⁹), and the galaxy's circular velocity (Ferrarese¹⁵). The proposed scenario does not, in itself, naturally predict such an effect, although it does not exclude it either.

5. Summary

We have discussed a model for the origin of quasars in which a major merger of galaxies results in the creation first of a central self-gravitating accretion disk. In such an environment, under the influence of hydrodynamically induced β -viscosity,

the disk evolves much more rapidly than predicted by standard (α -)disk theory. This evolution leads through three stages, namely first Eddington-limited, then free, and finally advection dominated accretion. The model seems capable of explaining the early epoch of the first quasars, their epoch of peak activity at redshifts around $z \sim 2$ and their subsequent rapid disappearance. The proposed scenario provides not only the fuel for the quasar phenomenon but also the creation of the SMBH engine.

Acknowledgments

WJD acknowledges generous support from Steward Observatory and from the Deutsche Forschungsgemeinschaft through SFB 439.

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